Lifetime of the $1s2p$ $^1P_1$ excited level in Fe^{24+}

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Abstract. Measurements of the spectrum of Fe^{24+} in the 1.845 Å to 1.885 Å range obtained on the EBIT-I electron beam ion trap at Lawrence Livermore National Laboratory were used for determining the radiative lifetime of the 1s2p $^1P_1$ excited state. The spectrum contains electric dipole forbidden transitions at 1.855Å ("x") and 1.868Å ("z") whose lineshape is well represented by a Gaussian line profile and is assumed to be due primarily to Doppler and instrumental broadening. The Gaussian contribution is assumed to be the same for all lines in the spectrum. This assumption simplifies the problem when considering a more complex combination of broadening mechanisms. For allowed transitions such as $1s2p$ $^1P_1 \rightarrow 1s^2$ $^1S_0$, "w", at 1.850 Å we assume a Voigt profile. In the simplest case this combines both natural (Lorentzian) and Doppler (Gaussian) broadening effects which contribute to the width of the spectral line. With the Gaussian contribution determined from lines "x" and "z", deconvolving the Gaussian from the Voigt profile gives the natural line width. This then is directly related to the radiative lifetime of the 1s2p $^1P_1$ excited level.

INTRODUCTION

The natural line width demonstrates the uncertainty in the discrete energy levels of a bound electron. There is a corresponding time uncertainty given by Heisenbergs' uncertainty relation [1, 2].

$$\Delta E \Delta t = \frac{h}{2\pi} \qquad (1)$$

For the $1s2p$ $^1P_1 \rightarrow 1s^2$ $^1S_0$ transition, the lower energy level is the ground state, which has no energy uncertainty. This implies that ΔE in Eq. (1) is the energy spread for the upper level in this transition and so Δt is the lifetime of the electron in the upper energy level. The energy uncertainty, ΔE, can also be written

$$\Delta E = h\frac{\Delta\omega}{2\pi} = hc\frac{\Delta k}{2\pi} = hc\Delta\left(\frac{1}{\lambda}\right) = hc\frac{\Delta\lambda}{\lambda^2} \qquad (2)$$

where λ is the peak wavelength for the spectral line of interest. Putting this form into Eq.(1) we build an expression for the mean amount of time the electron spends in the excited state in terms of the measureable quantities λ and $\Delta\lambda$,

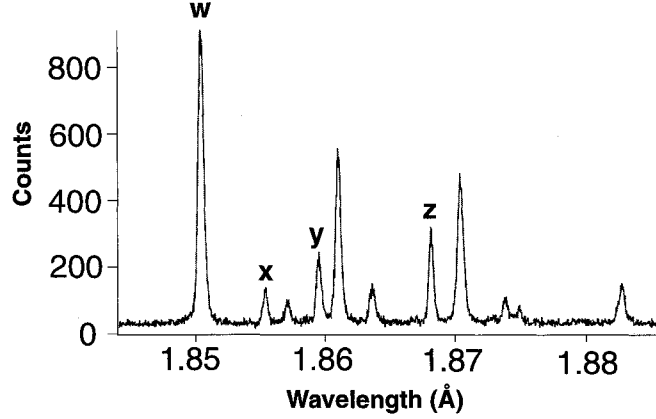$$\Delta t = \frac{\lambda^2}{2\pi c \Delta\lambda} \qquad (3)$$

FIGURE 1. Spectrum of K-shell emission lines from heliumlike and lithiumlike iron ions. The transitions in heliumlike ions labeled w,x,y,z correspond to the transitions from $1s2p\ ^1P_1$, $1s2p\ ^3P_2$, $1s2p\ ^3P_1$ and $1s2p\ ^3S_1$ levels to the $^1S_0$ ground state, respectively.

A measurement of the natural linewidth thus can be exploited to derive the upper level lifetime. To our knowledge, this method had not been used previously to determine the lifetime of the $1s2p\ ^1P_1$ excited level.

EXPERIMENT

The spectrum of Fe^{24+} and the strong lines of Fe^{23+} in the 1.845 Å to 1.885 Å range (Fig. 1) was obtained on the electron beam ion trap (EBIT-I) at Lawrence Livermore National Laboratory by a von Hámos bent crystal (Si(400)) X-ray spectrometer [3, 4]. For observations of extended light sources this spectrometer requires an entrance slit. Here we make use of the fact that the light source, the electron beam, is as narrow, $50\mu m$ diameter, as the required slit for the spectrometer. So no physical slit is needed. The spectrometer offers a throughput comparable to that of more common focusing devices better suited for larger light sources (e.g. Johann type spectrometer [5]). In addition, a simultaneous coverage of a large wavelength band is possible. Iron pentacarbonyl $Fe(CO)_5$ was introduced into EBIT-I with a gas injector. The electron beam energy was 8.028 keV, with a beam current range of 80 to 130 mA, appropriate for creating a majority of He-like iron ions in the trap ($I_p(Fe^{23+}) \approx 2.04$ keV and $I_p(Fe^{24+}) \approx 8.82$ keV). The ion temperature, obtained from the Doppler relation

$$T_i = m_i c^2 \left(\frac{(\Delta E/E)^2}{8 \ln 2} \right) \qquad (4)$$

was ≈ 464 eV.

ANALYSIS

Model Fit

Test Gaussian and Lorentzian distributions were created and convolved to verify the fitting method used. The Gaussian form used was as follows,

$$Gaussian_{MOD}(\lambda_D) = exp^{-\left(\frac{1}{2}\left(\frac{\lambda_D}{\sigma}\right)^2\right)}$$

(5)

with $G_{FWHM} \equiv \Delta\lambda_D \equiv 2(2\ln(2))^{\frac{1}{2}}\sigma$, the full width at half maximum for the Gaussian line shape and σ is the standard deviation defined by

$$Gaussian_{MOD}(\lambda_D = \pm\sigma) = exp^{-\frac{1}{2}} Gaussian_{MOD}(0)$$

(6)

The Lorentzian form was,

$$Lorentzian_{MOD}(\lambda_N) = \frac{1}{\left(\left(\frac{2\lambda_N}{\Delta\lambda_N}\right)^2 + 1\right)}$$

(7)

with $L_{FWHM} \equiv \Delta\lambda_N$, the full width at half maximum for the Lorentzian line shape. A Voigt fit was then performed on the convolution of the two, returning the Gaussian and Lorentzian contribution to V_{FWHM}, the Voigt full width at half maximum. The fitting program allowed the width due to Doppler broadening to be chosen and held fixed. This allowed for a verification of the Lorentzian width origionally put in.

Results

The Doppler broadening must be the same for all Fe^{24+} lines. This was tested using two forbidden transitions, "x" and "z", that appear in the spectrum. The natural width of a forbidden transition should be vanishingly small providing a good scenario for determining the other broadening mechanisms. In this case only the Doppler broadening (and the broadening from the instrumental response) is considered to be significant. The Gaussian fits to "x" and "z" are shown in (Fig. 2 b) and c)). The tables show the Doppler contribution to "x" to be within $\sim 0.37x10^{-4}$ Å that of "z", verifying our

TABLE 1. The Lorentzian (natural) width of "w" using the Gaussian (Doppler) width determined from the forbidden transition, "z" and the corresponding lifetime for "w".

Voigt shape	$G_{FWHM}(\text{Å})$	$L_{FWHM}(\text{Å})$	$\Delta t(s)$
$0.34^{+.02}_{-.03}$	$4.10x10^{-4+8E-6}_{-8E-6}$	$1.67x10^{-4+8E-6}_{-1E-5}$	$1.09x10^{-15+6E-16}_{-5E-17}$

TABLE 2. The Lorentzian (natural) width of "w" using the Gaussian (Doppler) width determined from the forbidden transition, "x" and the corresponding lifetime for "w".

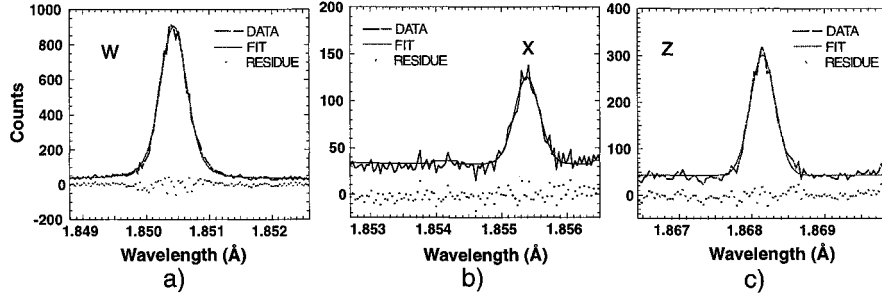| Voigt shape	$G_{FWHM}(\text{Å})$	$L_{FWHM}(\text{Å})$	$\Delta t(s)$
$0.25^{+.05}_{-.06}$	$4.37x10^{-4+2E-5}_{-2E-5}$	$1.30x10^{-4+2E-5}_{-3E-5}$	$1.40x10^{-15+4E-16}_{-2E-16}$

FIGURE 2. a) Voigt fit to "w" , b) Gaussian fit to "x", and c) Gaussian fit to "z".

contention that Doppler (and instrumental) broadening are the same for all Fe^{24+} lines. This allows some confidence when adopting this measured Doppler width for "w". The corresponding Lorentzian widths for "w" obtained by using the Doppler widths from both "x" and "z" separately were then used to determine two values for the lifetime of the $1s2p$ $^1P_1$ excited state in Fe^{24+}. The average of the two rather similar lifetimes gives a value of $1.24x10^{-15}$ s. This disagrees with the theoretical values of $2.18x10^{-15}$ [6] or $2.19x10^{-15}$ [7] by roughly a factor of two.

Neglecting all but the natural and Doppler broadening may be too much of a simplification. Any additional contributions to the width of the 1s2p $^1P_1$ excited state would decrease the natural width and thus increase the lifetime. Also, the data are a sum of many sets which could create a degradation in the resolution resulting in a slightly larger width in the final analyzed spectrum. One final approach to a more accurate result would be to decrease the ion temperature until the Doppler broadening contribution becomes negligible. This idea was successfully applied by *Beiersdorfer et al.* to Cs^{45+} to determine the lifetime of the 2p-3d transition [8].

ACKNOWLEDGMENTS

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